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?-Spread Due to Random Field Errors

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AD/RHIC–61

RHIC PROJECT

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1. Introduction

Previous work indicated that the random b_k, a_k, field errors can produce a large ν–spread within the beam.[1] For the worse case a ν–spread of $\Delta\nu = 21 \times 10^{-3}$ has been found.

Following the suggestion of A.G. Ruggiero, that the average value of b_k around the ring, $b_{k,av}$ may be responsible for the large $\Delta\nu$, it has been found that a major part of the $\Delta\nu$ can be corrected with a $b_{k,av}$ correction system. Nonetheless, with our present correction system, an appreciable $\Delta\nu$ may remain.

To keep a proper perspective on this problem, one should keep in mind the following aspects of the problem:

1) A small fraction, about 25%, of accelerators will have random error distributions that cause large ν–spreads.
2) The ν–spread computed below is for the beam dimensions after 10 hours of growth due to intrabeam scattering for the case of Au.
3) Only particles with large x and small y exhibit the large ν–shifts that cause the large ν–spread. This again is some fraction of all the particles.
4) The $\Delta\nu$ due to random errors is not simply additive to the $\Delta\nu$ due to the beam–beam interaction, $\Delta\nu \simeq 25 \times 10^{-3}$. The beam–beam $\Delta\nu$ is smaller at large betatron amplitudes, where the $\Delta\nu$ due to b_k, a_k is largest.

2. Results Before Corrections

The overall results are first presented, without much analysis or breakdown into contributions of different b_k, a_k. Later on the contribution of various b_k, a_k will be studied.

The following table lists the ν–spread found for 20 distributions of random field errors.

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[1] G. Parzen, AD/RHIC–AP–84, 1987.

$\Delta\nu$–Spread Due to Random b_k, a_k

Field Error Number	$\Delta\nu/10^{-3}$
1	3
2	2
3	4
4	4
5	10
6	2
7	4
8	3
9	2
10	2
11	0
12	7
13	1
14	7
15	0
16	1
17	4
18	9
19	2
20	14

$\beta^* = 6,\ x_o = 9.8$ mm, $y_o = 0,\ \epsilon_t = 1.92,\ \gamma = 30,\ \Delta p/p = \pm 0.005,\ x_o = \sqrt{10}\ \sigma$ after 10 hours for Au.

3. Results After $b_{k,av}$ Correction

A study of the contribution of the individual b_k, a_k errors to the ν–spread, showed that the $\Delta\nu$–spread comes almost entirely from the lower multipoles, a_2, b_2, a_3, b_3 and a_4, b_4.

In the tracking study, following Ruggiero's suggestion, $b_{2,av}$ $b_{3,av}$ and $b_{4,av}$ was subtracted in each dipole from the b_2, b_3 and b_4 present in each dipole. This reduced the ν–spread as shown in the following table.

Error Field Number	Uncorrected $\Delta\nu/10^{-3}$	Corrected $\Delta\nu/10^{-3}$
5	10	4
12	6	2
14	7	7
18	7	5
20	14	7

Results with Present b_2, b_3, b_4 Correction Coils

The previous results obtained through $b_{k,av}$ correction are probably not achievable, at present, for the following reasons:

1) The b_3, b_4 correction coils presently in RHIC can only remove about 1/2 of the ν–shift due to $b_{k,av}$.
2) The $b_{3,av}$ and $b_{4,av}$ present in the dipoles will probably be larger than that assumed in the previous results.

The expected $b_{k,av}$ in the tracking studies in the 144 dipoles is

$$b_{k,av} = \frac{1}{\sqrt{144}}\, b_{k,rms} = 0.085\, b_{k,rms}$$

The actual $b_{k,av}$ used is for field errors 20 and 5.

$b_{k,av}/b_{k,rms}$	Field Error 20	Field Error 5
b_2	-0.049	0.099
b_3	0.164	0.149
b_4	-0.053	-0.088

These results are similar to those found in Ruggiero's statistical analysis.[2]

One case was seen with $b_{k,av} = 0.26\, b_{k,rms}$. For the two worse field errors, number 20 and number 5, the largest $b_{k,av}$ is $b_{k,av} \simeq 0.16\, b_{k,rms} \simeq 1/6\, b_{k,rms}$.

It seems likely that one should expect to see $b_{k,av} \simeq (1/3)\, b_{k,rms}$. Doubling the $b_{2,av}, b_{3,av}$ in the dipoles, and assuming that only 1/2 of the ν–spread due to $b_{k,av}, b_{4,av}$ can be corrected gives the following ν– spreads.

[2] A.G. Ruggiero, AD/RHIC–86.

Field Error Number	Uncorrected $\Delta\nu/10^{-3}$	Corrected* $\Delta\nu/10^{-3}$
20	21	14
5	16	10

*With present correctors.

It appears desirable to have good $b_{3,av}$ and $b_{4,av}$ correctors.

4. A Possible Good $b_{3,av}$ and $b_{4,av}$ Corrector

One way to cancel the effect of b_3 in a dipole, is to have 3 b_3 correction coils, one at the middle of the dipole, and one at each end, with $\int dsb_3$ of the correction coils equal to $b_{3,av}$ times the dipole length.

In so far as the analytical results for $\Delta\nu$ due to b_3 are valid, the three correction coils can be anywhere in the lattice as long as they are at 3 places where β_x, β_y and X_p are the same as at the above mentioned 3 places in the main dipole in the arcs.

It has been suggested by J. Claus, that these 3 correction coils could be placed between Q9 and Q8 in the insertions as this space contains a region where β_x, β_y, X_p are similar to the β_y, β_y, X_p in the dipoles.

A further simplification is to have just one correction coil in the Q9 to Q8 space, at a place where β_x, β_y, X_p have about the same values as in the middle of the dipole, plus the present b_3 coils.

This proposed correction scheme needs to be tested by tracking studies. At this point, it appears to promise to provide a partial solution of the good $b_{3,av}$ correction problem.

The correction of $b_{4,av}$ can be treated in a similar way.

5. $\Delta\nu$–Spread, Not Correctable through $b_{k,av}$

Three possible sources of $\Delta\nu$–spread not correctable through $b_{k,av}$ are:

1) $\Delta\nu$ due to higher order terms in b_k, a_k
2) $\Delta\nu$ due to b_k, a_k in non–dipole magnets (e.g. quadrupoles, insertion dipoles)
3) $\Delta\nu$ due to b_k, a_k for $k \geq 5$

Examples of the first two effects are given below. The third effect was not observed for the 5 worse error fields that gave the largest $\Delta\nu$–spread.

Higher Order $\Delta\nu$ Due to b_2, a_2

For error field 20, the breakdown is as follows for the ν–spread, $\Delta\nu$

	$\Delta\nu/10^{-3}$
All b_k, a_k no correction	14
All b_k, a_k with $b_{k,av}$ correction	7
b_2, a_2 only, no correction	6
b_2, a_2 only with $b_{2,av}$ correction	6
b_3, a_3 only, no correction	5
b_3, a_3 only with $b_{3,av}$ correction	0
b_4, a_4 only, no correction	2
b_4, a_4 only with $b_{4,av}$ correction	1

The breakdown shows the presence of $\Delta\nu$ due to b_2, a_2. Computer study shows that for field error 20 this is a higher order effect as $\Delta\nu$ varies like the square of b_2. Further study indicates that this $\Delta\nu$ for field error 20 depends only on $\Delta p/p$ and not on ϵ_x. Thus it may be partly correctable by the 6–family b_2 correction system in RHIC, that can correct the quadratic term in $\Delta p/p$ in $\Delta\nu$.

For field error 18, the $\Delta\nu$ due to b_2, a_2 is $\Delta\nu = 4 \times 10^{-3}$ and was found to depend on ϵ_x and not much on $\Delta p/p$. This higher order effect may be more difficult to correct than the $\Delta\nu$ due to b_2, a_2 for field error 20. The three octupole correction coils, including the one between Q9 and Q8, may be able to correct this effect.

There are still some possibilities for correction by exciting the correction sextupoles in each sextant independently.

The higher order effect for $\Delta\nu$ due to b_2, a_2 can show itself either as a quadratic variation of $\Delta\nu$ with $\Delta p/p$ or as a linear variation with ϵ_x or ϵ_y, depending on which harmonics of the random a_2, b_2 are largest.

Non–Dipole Contributions to $\Delta\nu$–Spread

The 5 worse field error distributions were tested for contributions to $\Delta\nu$ from magnets other than the main dipoles in the arcs. Field Error 14 showed a $\Delta\nu$ of $\Delta\nu = 4 \times 10^{-3}$ from non–dipole sources.

$\Delta\nu$–Spread Due to $b_k, a_k, k > 5$

For the 5 worse cases studied, the b_k, a_k for $k \geq 5$ were found not to contribute to the ν–spread. Correction coils for b_k for $k > 5$ do not seem to be needed.

$\Delta\nu$–Spread and the Effect of Coupling

Because the operating ν–values are close to the resonance line, $\nu_x = \nu_y$ a modest amount of the skew multipole, a_k, will completely couple the horizontal and vertical betatron oscillations. The effect of this on the ν–spread is to almost double the ν–spread, in many cases, caused by the normal multipoles, b_k.

The larger ν–spread due to coupling may be partly understood in the following way: a b_k, when no a_k is present, would generate a ν–spread of $\Delta\nu_x$ in the x–motion and $\Delta\nu_y$ in the y–motion, where $\Delta\nu_x$ and $\Delta\nu_y$ are usually not too different. Because of the complete coupling, any growth in the x–motion due to $\Delta\nu_x$ is also felt by the y–motion, and one might say that the effective ν–spread is $\Delta\nu_x + \Delta\nu_y$.

This effect shows itself in the tracking in that, because of the coupling, both the x–motion and the y–motion contain 2 modes with ν–values ν_1 and ν_2. The random b_k, a_k generate a spread in both modes $\Delta\nu_1$ and $\Delta\nu_2$ with a total spread of $\Delta\nu = \Delta\nu_1 + \Delta\nu_2$.

Conclusion

The ν spread due to random b_k, a_k may be a large effect when uncorrected. In the worst case, the ν–spread may be as large as $\Delta\nu = 21 \times 10^{-3}$. It appears important to have a good $b_{k,av}$ correction system for $k = 3, 4$. Higher order contributions to $\Delta\nu$ from b_2, a_2 are appreciable. With some modification of the present b_3, b_4 correction system, and with some luck and skill in reducing the ν–spread not correctable through $b_{k,av}$, one may be able to reduce this ν–spread to about $\Delta\nu = 4 \times 10^{-3}$.

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